Assessing the efficacy of passive measures for the tropical context of Mauritius through parametric simulations and in-situ measurement

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Abstract
The transition from the traditional creole typology to the modern concrete vernacular structures has taken place progressively over the past few decades in Mauritius, motivated by the need for cyclone resistant buildings. However, the lack of consideration for thermal properties of the wall, glazing and roof construction has resulted in interior space conditions generally uncomfortable during summer conditions, evidenced by the increasing installation and use of air conditioning systems. With summers projected to become warmer due to climate change, passive design measures should be re-incorporated into existing and new constructions to decouple active cooling and urbanisation. This paper describes the parametric analyses carried out to generate cooling load (peak and coincident) for wall, glazing and roof components and temperature (operative, radiative and air) variations for a test building model made up of nine rooms, of which eight were peripheral and one central (with no external walls). The simulations were undertaken in Designbuilder® for a base case with no passive measures and for various low cost passive measures – overhang of various depths, external vertical shading and curtains, roof shading and planting tall trees around the building, incrementally rotated. The results allowed to assess the efficacy of each passive measure, validated against experimental data collected in actual buildings. The study also provided much needed quantitative data on surface and air temperatures prevailing inside buildings, which are key to bringing about the needed shift in mindset and the construction market.

Keywords Thermal Comfort, Passive Design, Energy Performance, Sustainability in Built Environment.

1.0 Introduction

The built environment in the tropical island of Mauritius is largely reliant on concrete fabric, with concrete blocks available in 125mm (4”), 150mm (6”) and 200mm (8”) widths, used as non-structural wall element whereas cast concrete beams and columns, reinforced with steel bars of suitable diameters, provide the structural integrity needed. Indeed the shift from the traditional creole typologies, which used effective passive measures such as shading with terraces and air vents to promote continuous ventilation through the interior spaces, has been motivated by the need for cyclone resistant building structures. Indeed, it can be safely said that the nation is better equipped to deal with cyclones, but not when it comes to providing human comfort.

The increased reliance on air-conditioning to provide comfortable indoor conditions has been clearly evidenced over recent years, and this had a direct impact on the carbon footprint of the built environment to the extent of putting unprecedented load on the electricity grid. The peak summer periods have witnessed more frequent power cuts, and given the high carbon emission rating of the local electricity production process (with around 80% derived from burning coal and heavy oils and the remaining 20% generated from renewable sources, mainly bagasse, hydro, wind, solar and landfill gas [1], rated at around 1 $kgCO_2/kWh$, there is a pressing need to decouple the carbon footprint of the built environment with economic growth as Mauritius aspires to transition into a high-income economy so that the accompanying urbanisation is laid on sustainable terms.

1.1 Passive design for thermal comfort and energy efficiency

Passive measures relate to the design of building elements which allows to regulate the indoor environment, with the goal to achieve suitable conditions by harnessing natural resources available at the project site as much as possible, while preventing these natural resources from adversely affecting the indoor conditions. One of these goals is heat regulation, which can mean limiting or promoting heat gains for certain regions and/or periods of the year. The increased use of air-conditioning in Mauritius certainly points to a need to limit heat gains predominantly, although (1) the presence of micro-climates, (2) the possibility of significant variation in insolation level at a given location over a day, and (3) regions with both cooling requirement in summer and heating requirement in winter means that adaptive control of the passive measures with respect to the prevailing climate and indoor conditions needs to be considered. Furthermore, Gooroochurn et al. [14] noted a diurnal temperature variation from a maximum of 32°C during the day and a minimum of 19°C in the peak summer month of February, showing the potential to use effective passive measures like night cooling to flush interior spaces and building fabric to drive away accumulated heat.

With the advent of renewable energy sources at affordable prices and increasing efficiency of conversion, their integration into the energy mix of buildings can be seen as an effective move to green the built environment, but renewable energy should be considered when the energy efficiency has been optimised with due consideration of passive design and building energy systems control, as depicted in Figure 1. For large projects, this optimisation process calls for an integrative design paradigm, as supported by green building certification frameworks such as BREEAM [2] and LEED [3]. Revisiting the good design practices in our traditional construction seems an effective approach to take as proven in past studies comparing traditional and contemporary architectures. A study by Tinker and Ghisi [4] in Malaysia showed the better performance of a traditional Malay house compared to a modern low-income house.

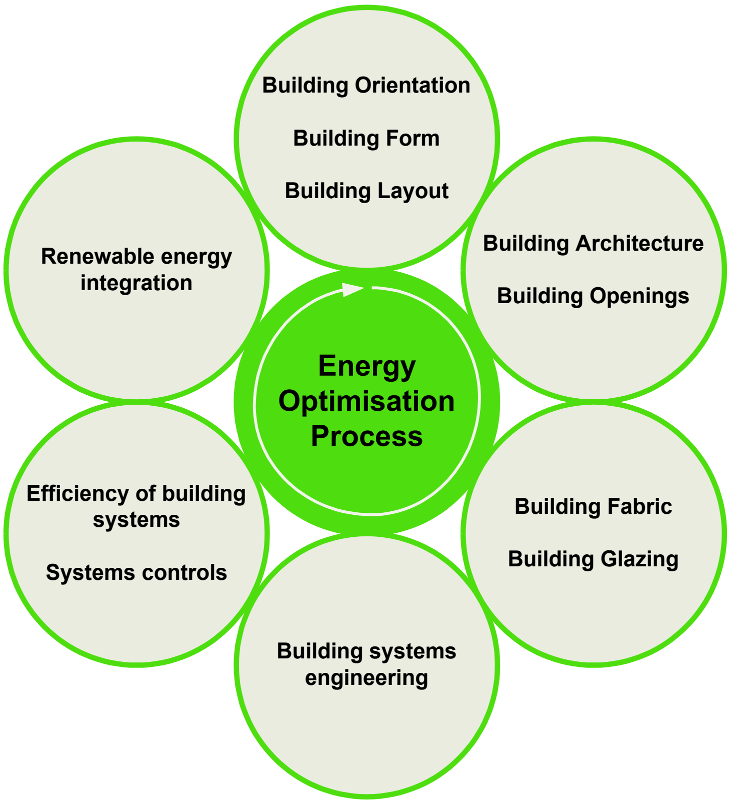


Figure 1: Energy optimisation process for building projects

The complex interaction between the factors affecting energy and mass transport into the building via the envelope has prompted the use of building simulation packages for predicting the expected performance of design concepts. Several studies [5, 6] have shown the efficacy of such simulations in obtaining calibrated or comparative performance data. Daylight penetration and controlling heat gains is an important trade-off in the design of building features, where the Window-to-Wall Ratio (WWR) has been investigated extensively to set thresholds for the WWR and to understand the influence on thermal comfort and building energy performance [7, 8].

Considering passive measures in a more holistic manner, studies [9, 10, 11] have unanimously demonstrated that shading is the most effective strategy to achieve thermal comfort in warm and hot climates, with simple use of curtains found to yield 40% reduction in cooling load. The shading strategy takes greater prominence for roofs, especially for flat roofs, which is predominantly the case in Mauritius as pitched roofs are costlier to construct and reduces buildable area for future extensions. In addition to shading of roofs, measures to modify the thermal properties of the roof construction itself have been investigated as a cool roof [12] and green roofs, although these measures are permanent and do not allow an adaptive control of the heat transfer dynamics.

The renewal of oxygen and heat transport by air movement through building spaces is another passive measure that has been beneficially applied to foster occupant comfort with high levels of energy performance [13]. The buoyancy effect of warm air has been used in double skin façade to provide beneficial heating in colder climate zones, and as a means to drive out heat amassed in the building structure. In this respect, Gooroochurn et al. [14] investigated the use of a space saving ventilated façade using hollow cavity concrete blocks to prevent the build-up of heat in the concrete structure passively, and achieved as much as 6°C reduction in interior wall temperature in the west orientation, known to be particularly heat intensive due to the settling sun. This buoyancy effect can be applied in conjunction with ground-coupled heat exchanger systems to further temper the air admitted into the building interiors [15, 16, 17].

The findings from literature confirm the primary need to carry out an optimisation of the building performance using passive design approaches in the first instance before considering active energy systems, if there is a need for it, and subsequently renewable energy integration. When it comes to homes, which is the focus of this research work, low tech and manually adjustable passive features need to be considered. In view of assessing the efficacy of the passive measures reported in literature, in the tropical context of Mauritius, a simulation approach was adopted to be able to provide recommendations for households to limit, if not eliminate the need for air-conditioning systems.

2.0 Methodology

The special focus of this research work is on residential buildings, where advanced simulations cannot be expected on a case-by-case basis, for which prescriptions have been generally used worldwide. However, these prescriptions need to be adapted to the local context, given the uniqueness of the climate, building materials and construction culture, in addition to the specific building layout. Another important constraint is that imposed by plot geometry, which means it is not always possible to construct according to an ideal layout. For example, given the solar path for Mauritius (see Figure 2), it is well known that eaves and overhangs can be used in the north orientation to block high elevation angle summer sun, and if desired allow lower elevation angle winter sun to penetrate through the glazing, by appropriately sizing the depth of these architectural elements, giving the ideal layout depicted in Figure 3. The longer side of the layout is aligned along the North due to the ease of blocking or allowing direct solar radiation whereas the shorter side is sited along the east and west orientations due to the difficulty in regulating heat gains from the low angle sun in these directions.

To understand the complex building physics and evaluate the efficacy of passive measures in the continuum of façade orientations imposed by plot geometry, a simulation approach was adopted first to generate parametric analyses, which were subsequently compared to experimental data for selected passive measures. The simulation was carried out in Designbuilder® with the building model illustrated in Figure 4, which consists of a 3x3 array of building interior spaces, numbered from 1 (facing north in the original model) to 9, where the latter is an interior space without any external wall. The spaces 1 to 8 have external walls, with the odd-numbered spaces having only one window surface since there is only one external wall for these rooms, and even-numbered spaces having two external walls, with each having a glazing in a corner configuration. The basis of creating such a hypothetical layout is that, rotating by suitable increments through a full 360° degrees, yields configurations of spaces which will be encountered in practice for actual building layouts. Being able to set recommendations for regulating heat transfer for these individual room spaces means a similar exercise can be carried out for a given building layout by segmenting the design into discrete elements, each with its own set of recommendations.

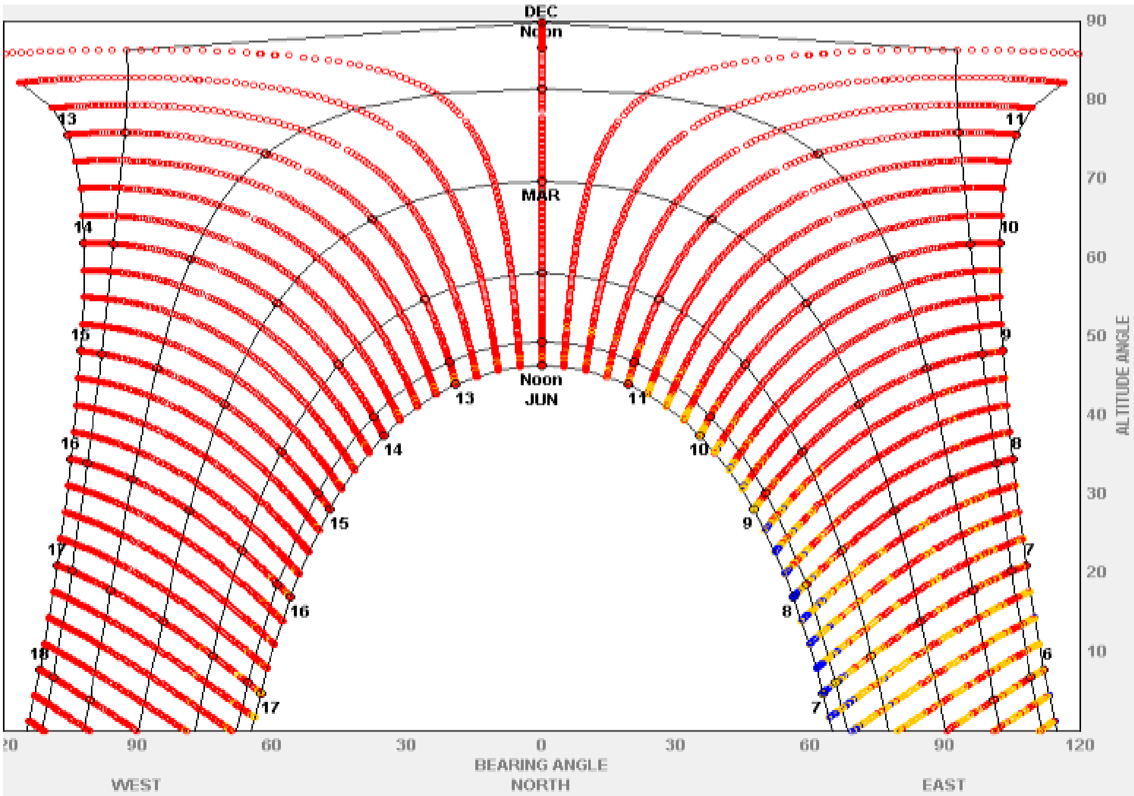


Figure 2: Solar path for Mauritius (generated from EPW Meteonorm® file for Mauritius using Climate Consultant)

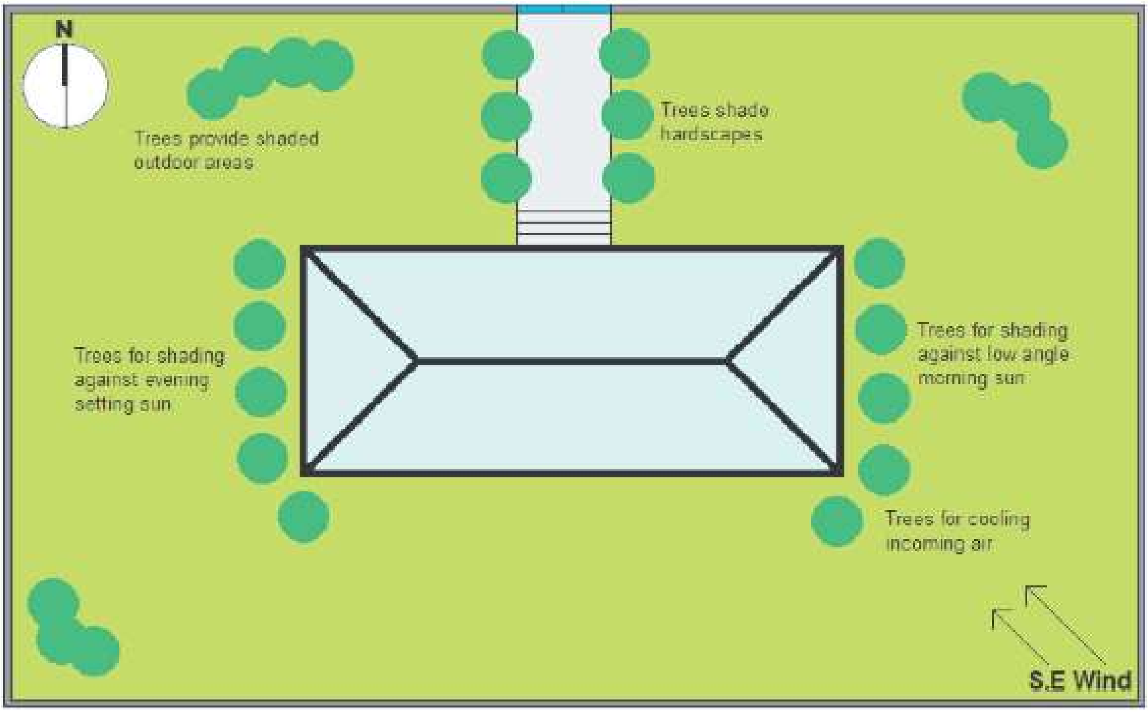


Figure 3: Ideal layout with major axis aligned along East-West

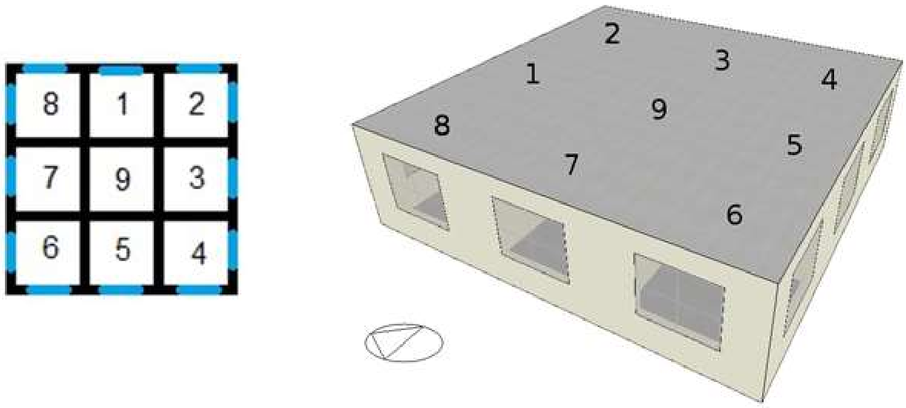


Figure 4: 3x3 space layout used to assess passive measures and controls

Although the complex interaction of the heat gains between the various spaces is not expected to be a simple linear combination of the individual phenomenon, the approach adopted is that of dealing with the heat transfer dynamics, either limiting an undesirable heat gain/loss or promoting a desirable one, at source so that the cumulative effect will promote the achievement of the desired interior conditions. For this reason, the interior partitions between these spaces have been made adiabatic by specifying a very high R value. A baseline case with no passive measures was generated, followed by configuration of the following passive measures:

- External shading devices for high angle and low angle sun
- Internal shading by using curtains
- Pitched roof
- Roof shading

The base case and few passive measures incorporated to it are illustrated in Figure 5.

3.0 Simulation results and deductions

This section presents the various parametric analyses performed and the associated analysis of the efficacy of each measure with respect to orientation. The first series of simulation results pertains to the design week simulation for peak summer conditions to analyse both the dynamics and static peak heat gain conditions. Since the overall aim of the project is to seek means to control heat gains to the building interiors, the base case is first analysed to set benchmarks for comparing all the other variations, while also understanding the effect of layout on the implications for heat gains to the interior. The heat gains are analysed for each element (wall, glazing and roof) so as to have a better understanding of the influence of a given passive measure; the complexity of the thermal phenomena involved means prediction based on simple logic cannot be applied. It is precisely to capture this complex interaction that a building simulation Integrated Development Environment (IDE) like Designbuilder® allowing advanced dynamic simulations has been used for the research. Based on the layout used with peripheral spaces having either one (odd-numbered rooms, except room number 9, which is a central space with no external wall) or two (even-numbered rooms) glazed openings, graphs illustrating the results are likewise presented in pairs for these odd- and even-numbered spaces.

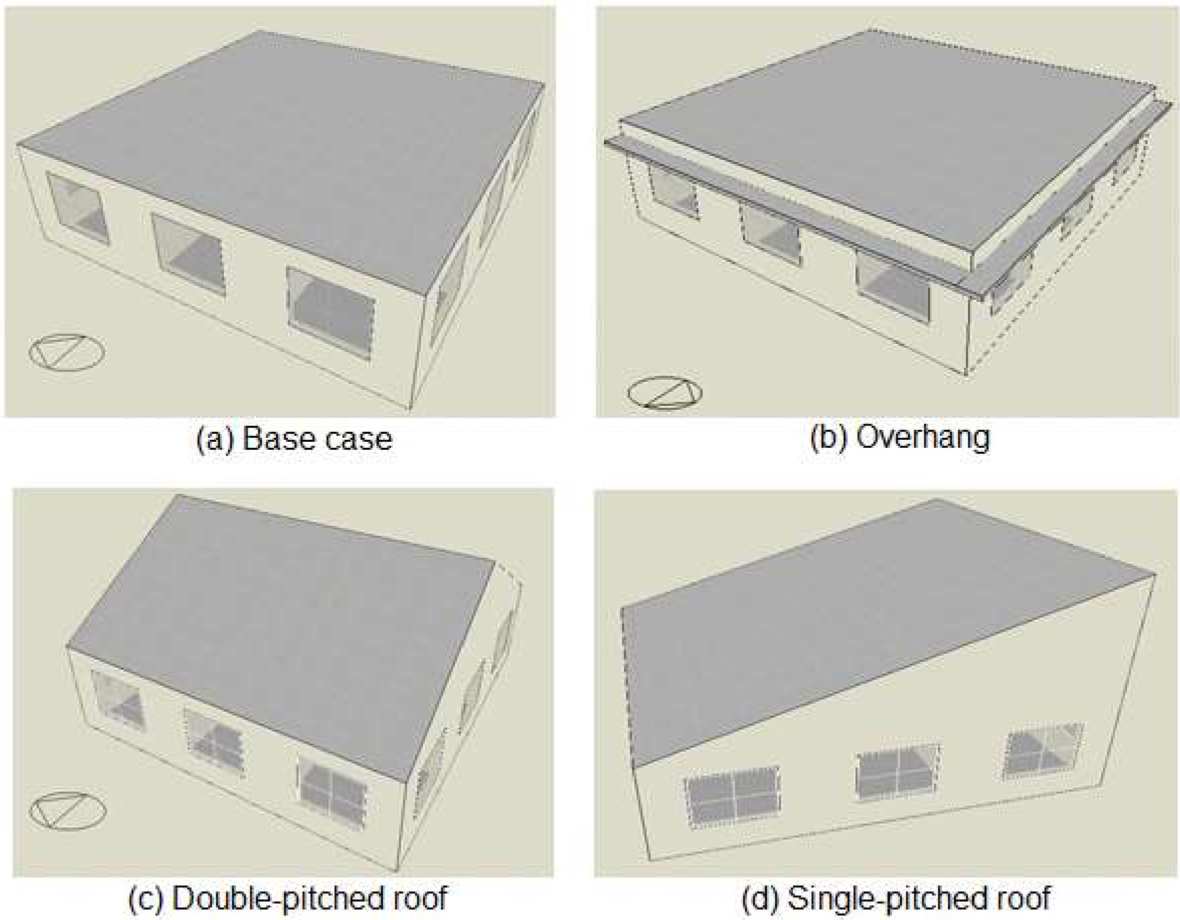


Figure 5: Simulation models (a) base case, (b) overhang, (c) double-pitched roof, (d) single-pitched roof

3.1 Design week analysis

3.1.1 Base Case

The simulation results obtained for the base case are illustrated in Figure 6, where the peak cooling load (PCL) through the window, roof and wall are plotted for the various rooms. In both even- (right graph) and odd-numbered (left graph) rooms, the significant source of heat gains through the glazing is clear whereas the heat gains through the roof remain more or less constant, with a connection observed with increased heat gains through the wall leading to lower heat gains through the roof. The increased direct solar gains through glazing in orientations with low solar angles (close to east and west) are observed.

The flat roof in Mauritius is found to be an important source of heat gains. The relative variation of peak heat gains through the glazing for the odd-numbered spaces (with one glazing surface) is found to be greater ranging from over 1600W to 400W (reduction by four), whereas even-number spaces had a variation in peak heat gains through the glazing ranging from around 2200W to 1000W (reduction by a factor of around 2). This shows the complexity in controlling heat gains to achieve thermal comfort in corner rooms, especially when located at orientations oblique to main cardinal directions.

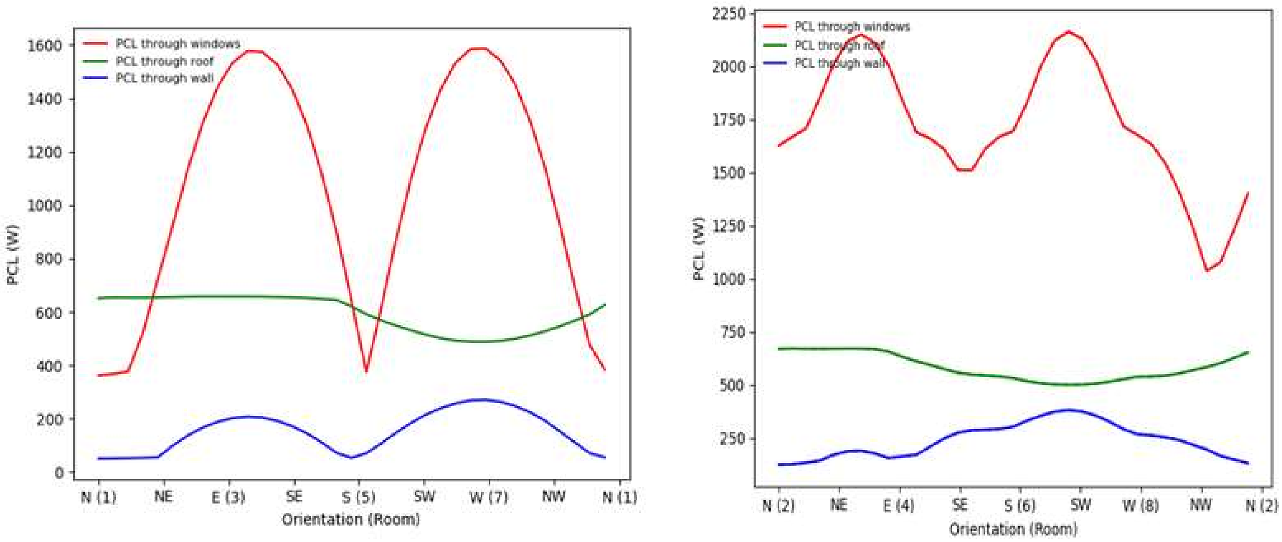


Figure 6: Peak cooling load (PCL) for base case with rotation, left plot showing odd-numbered rooms with one glazing only and right plot showing even-numbered rooms with two glazed openings.

3.1.2 External Shading: Overhang

The next parametric analysis relates to the use of overhang, which is known to be efficient in blocking direct solar radiation originating from high elevation solar angles, but quantitative data on the extent to which they are effective are generally lacking. Furthermore, their efficacy in rooms with different configuration of glazed opening is difficult to understand as well as with respect to orientations other than the main cardinal directions, which are typically the case due to site constraints. The profiles obtained for the odd- and even- numbered rooms are illustrated in Figure 7 for three depths of overhangs, namely 0.5m, 1.0m and 1.5m. The base case is represented in dashed line type in this and all subsequent parametric analyses to serve as benchmark.

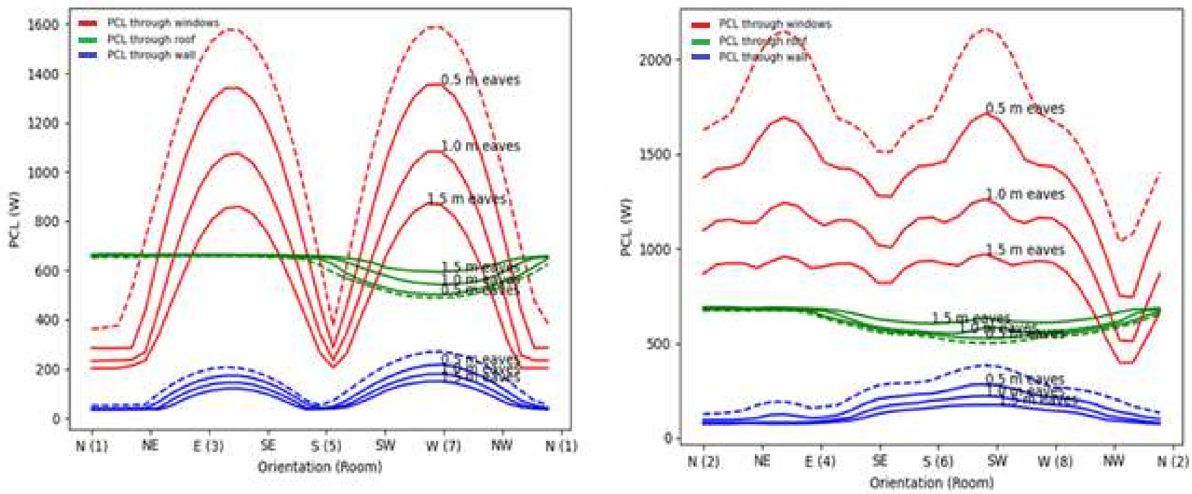


Figure 7: Peak cooling load (PCL) with 0.5m, 1.0m and 1.5m overhangs (dashed lines show the base case)

The overhangs are found to have beneficial heat gain reduction for the walls for low solar elevation angle orientation, although this is accompanied by an increase in heat gains through the roof. However, in terms of the radiative effect caused by walls, this measure is expected to yield to better thermal comfort, provided the concomitant increase in heat gains through the roof is controlled. As noted by Gooroochurn et al. [14], the inner wall surface temperature of concrete block construction with direct exposure to the sun can exceed 35°C, and given that the overall temperature experienced by an occupant is the average of the surface and air temperatures, it is clear that elevated wall temperatures should be avoided in addition to limiting heat gains to the interior spaces.

Although it is expected that overhangs will have a beneficial effect for high solar elevation angle, it is also observed that they help in reducing the peak heat gains through glazing by more than halving the peak heat gain through glazing at low solar elevation angles. This can be explained by the ability of the overhang to block direct solar radiation as the elevation starts to increase, thus reducing the cumulative effect of heat gains in a high thermal mass construction like concrete. Therefore, having overhangs of at least 1m will help significantly in reducing heat gains, and conversely in colder regions of Mauritius, having an overhang of 0.5m will be a good balance between limiting and allowing in heat gains. Furthermore, any means to modulate the depth of the overhang either automatically or manually, or to remove the overhang altogether during winter periods will be beneficial for colder climates.

3.1.3 External Shading: Vertical Fins

The next parametric analysis relates to simulating the effect of vertical fins as a fully opaque element over the windows, meaning that some form of automatic control of fins will be required in practice. This idealistic scenario serves to understand the dynamic influence of the nullifying the heat gains through glazing on the other two elements, that is, the wall and the roof, which are made of concrete, and hence have high thermal mass, known to accumulate heat during the day and lead to thermal discomfiture during late afternoon hours by the radiative effect. As illustrated in Figure 8, being directly exposed to the sun throughout the day, the roof is found to let in more heat gains, and this in turn causes a reduction in heat gains through the wall. Therefore, any measure allowing to control heat gains through the roof in conjunction with limiting direct solar gains through the glazing will have a beneficial overall effect.

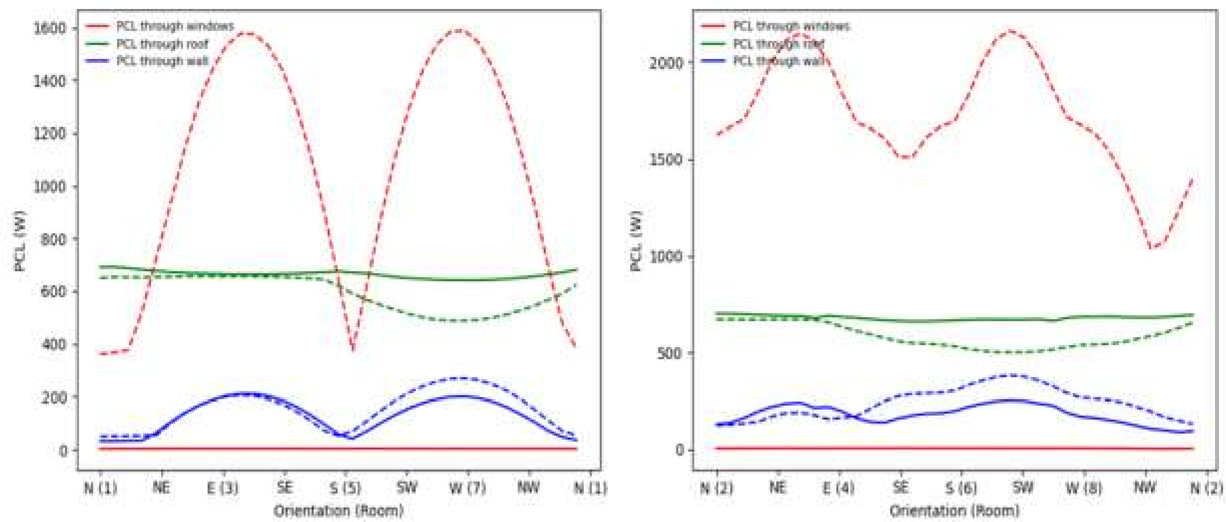


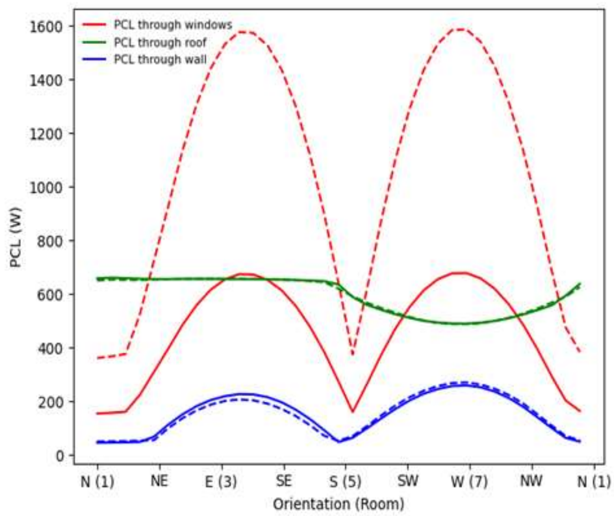
Figure 8: Peak cooling load (PCL) with external shading on windows (dashed lines show base case)

3.1.4 Internal shading: curtains

The ability to install external shading devices for windows may prove to be a costly expenditure and one at the risk of being damaged during cyclones. Therefore, the effect of having curtains has been studied as a low cost retrofit or improved awareness on the use of curtains for regulating heat transfer to the interiors. The default parameters for curtains available in Designbuilder were used, namely:

- solar transmittance 0.4
- solar reflectance 0.2
- visible transmittance 0.4
- visible reflectance 0.2
- IR thermal emissivity 0.9
- IR thermal transmissivity 0
- Thickness 0.005 m
- Conductivity 0.1 W/mK

The results obtained are depicted in Figure 9. The heat gains to the interior spaces through the glazing is found to reduce by more than 50%, with negligible influence on the heat transfer dynamics through the roof and the wall. The marked reduction is along the low solar elevation angle orientation, both for the odd- and even-numbered spaces. This shows the importance of coordinating curtains properly in spaces with two windows (even-numbered spaces) as any solar radiation allowed in will be sufficient to cause significant heat gains. In addition to analysing the profiles from a peak heat gains perspective, the effect of radiative heat as a result of elevated surface temperatures need to be considered as well, hence curtains along the north, and similar high elevation solar angle orientation will help in blocking the radiative heat from reaching the occupants.



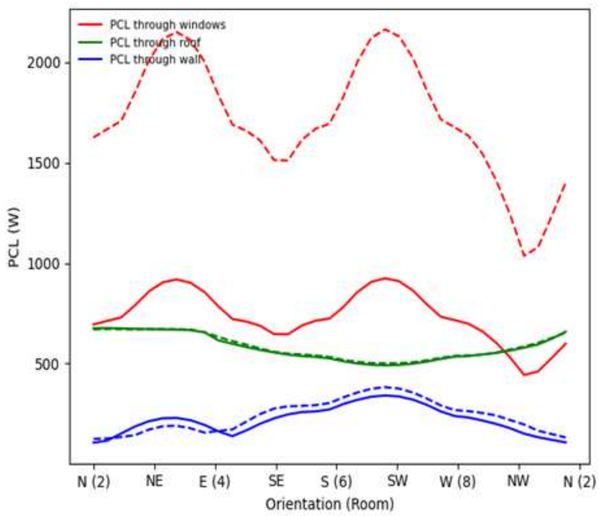


Figure 9: Peak cooling load (PCL) with curtains (dashed lines: base case)

Therefore, having high reflectance (low-coloured) curtains, able to block direct solar radiation when the sun is in direct line of sight prove to be a low cost and effective means to control heat gains adequately. As is usual in homes, where occupants may not be at home during the day, leaving curtains open when it needs to be closed or vice versa to allow beneficial heat gains can cause thermal discomfiture, especially in summer conditions in west facing rooms, where the build-up of heat in structures causes significant thermal stress to occupants in the evening. Therefore, again a low-cost, intelligent control system to deploy or retract the curtains will serve good purpose in homes.

3.1.5 Pitched roof

The fact that roofs are predominantly flat means that the sun shines on the roof surface throughout the day, amassing heat and increasing the surface temperature, and this is well-known to be the main reason for thermal discomfort in spaces with exposed roofs. The changes in the heat gains with the single (20° angle) and double (30° angle) are illustrated in Figure 10 and Figure 11 respectively, It is found that both roof configurations lead to marginal benefit for certain orientations for both odd- and even-numbered configurations for the single pitch, with the same trend observed for the even-numbered configurations with a double pitch. However, there is a clear reduction for odd-numbered spaces with double pitch for all orientations, although the reduction is not significant.

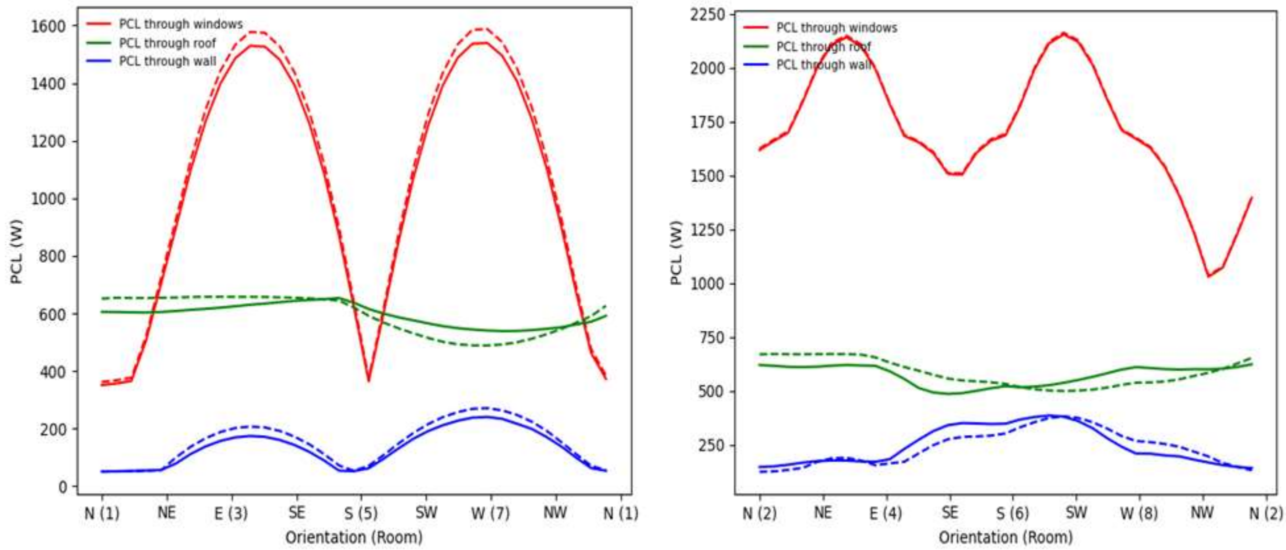


Figure 10: PCL with single-pitched roof (dashed lines: base case)

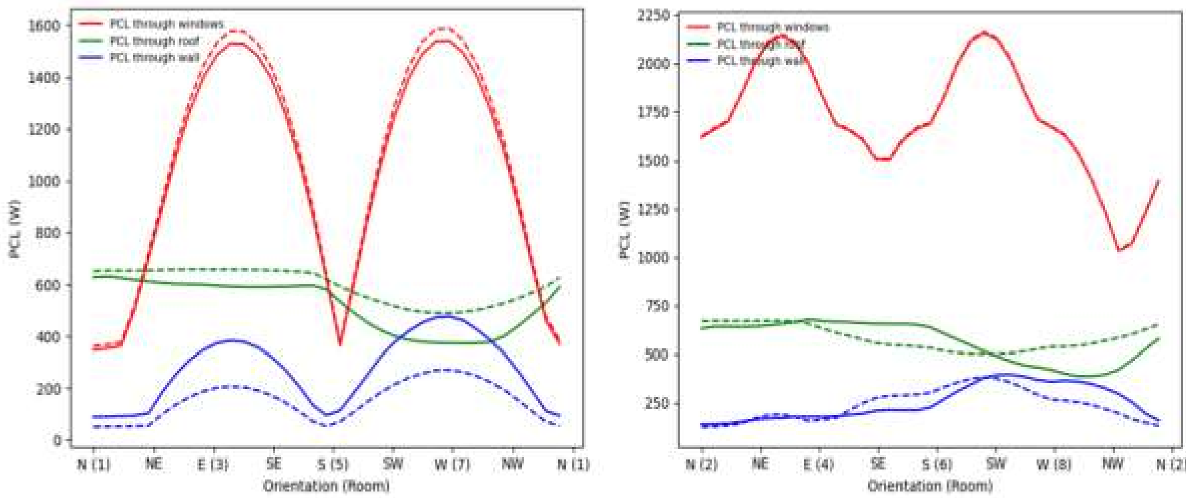


Figure 11: PCL load with double-pitched roof (dashed lines: base case)

3.1.6 Roof shading

The next parametric analysis considered was for shading the roof using an external surface, which could take the form of a permanent metal structure to create a terrace over the roof or a simple canvas which can deployed and taken off whenever needed. The shading device shields the roof surface from direct solar radiation, but does not prevent heat gain through conduction, which takes place whenever there is a temperature difference between the ambient and the interior space. Shading the roof is found to be beneficial for all configurations of rooms, with a significant reduction. As expected, the direct solar heat gains through the glazed surfaces are unaffected, whereas the dynamics of heat transfer through the wall changes, with an increase in heat gains for the latter. As shown in Figure 12, a marked reduction in peak heat gains through the fabric is observed, and this passive measure is deemed to be particularly effective for the flat, cast-concrete roofs. This confirms the high importance allocated to shading in warm and hot climates, typically referred to as cool building strategies.

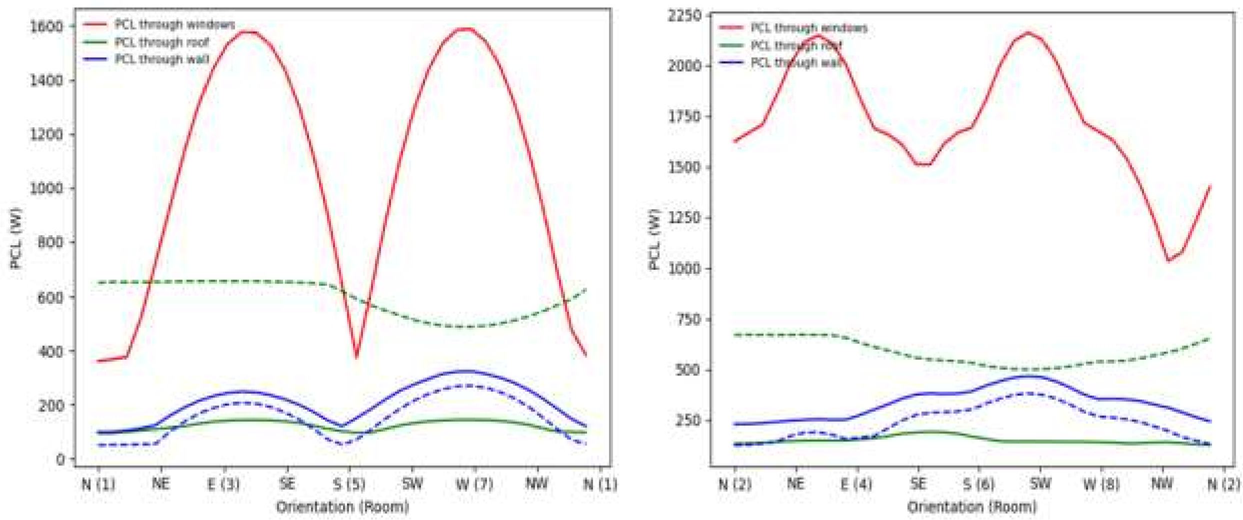


Figure 12: PCL with roof shading (dashed line: base case)

3.1.7 High reflective roof

A high reflective roof refers to the finish of the roof, which is lightly-coloured with a high solar reflective index (SRI) value. The default cool roof construction in Designbuilder was used to test its efficacy for the flat roofs and with the established thermal dynamics by the baseline building. The results are illustrated in Figure 13. A significant reduction in peak heat gains is again observed for all configurations of rooms and for all orientations, comparable to the results obtained with roof shading.

The use of reflective products is possible in Mauritius as reflective paints are available and previous research work in Mauritius to compare these products has shown marked improvement in solar reflectance and emissivity values, hence replicating the potential reduction in heat gains to the interior spaces by treating the roof surface is achievable at reasonable costs. This will be found to be largely beneficial in warmer regions of Mauritius, typical around the coast and on lower grounds. However, due to the reflective roof being a permanent measure, its implementation for colder regions, typically on higher, central regions of Mauritius is not recommended as this will lead to colder temperatures during winter periods, exacerbating the need for heating.

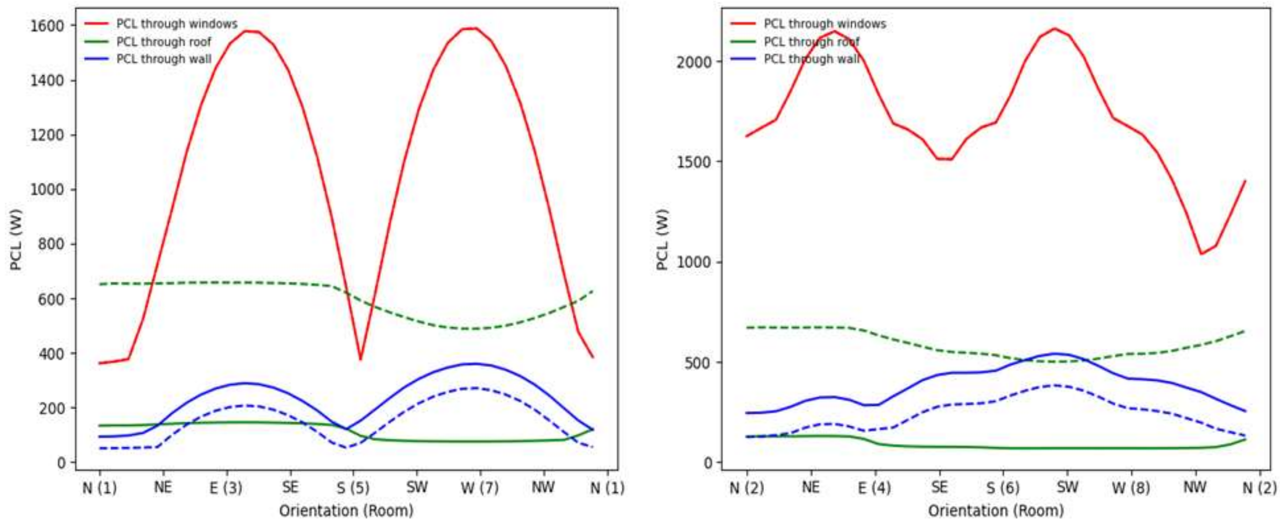


Figure 13: PCL with high reflective roof (dashed line: base case)

3.1.8 High reflectance wall

Given that wall construction in homes are made of hollow concrete blocks (predominantly 6" thick), rendered on both sides with mortar of around 10 mm, it is customary for buildings to be painted externally and internally, and this parametric analysis refers to using lightly coloured materials, as opposed to darker colours close to the natural grey colour of mortar finish. As observed in Figure 13, even if not at the scale of reflective roofs, the reduction in heat gains across all types of room combinations and orientations will be beneficial, especially for walls facing orientation with low to medium solar elevation angles, e.g. East and West. The associated increase in roof heat gains can be dealt by shading or similarly painting the roof surface, depending on the overall need to limit exclusively or at certain periods of the year.

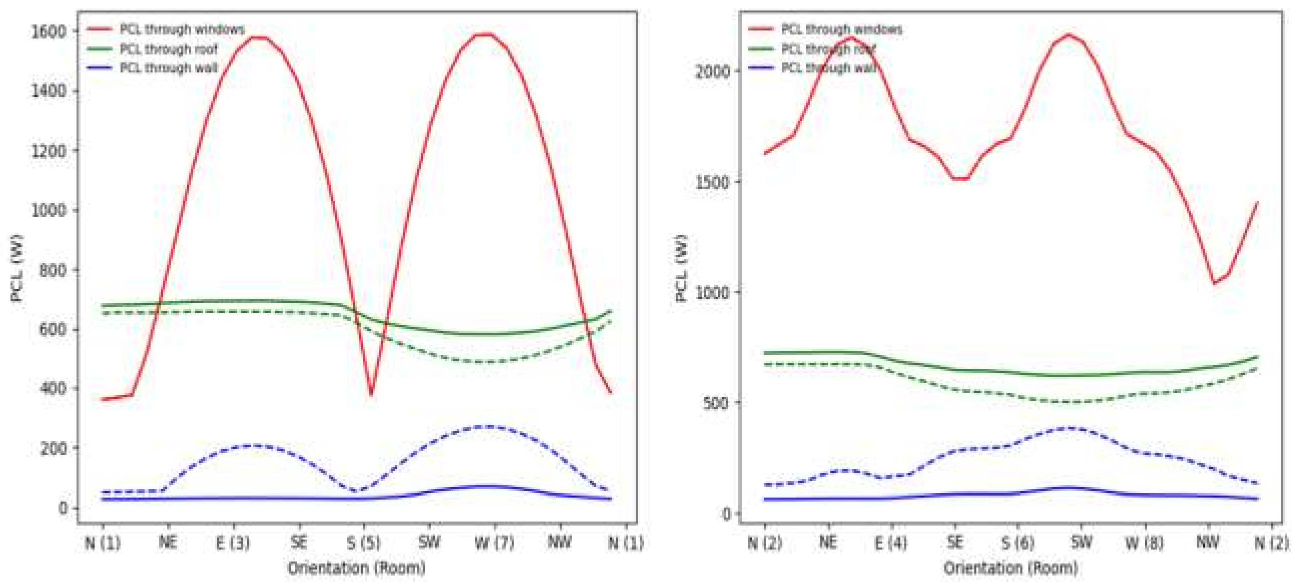


Figure 13: PCL with high reflectance wall (dashed line: base case)

3.2 Yearly analysis

Based on the results obtained with the design week simulations above over summer periods, a yearly simulation was carried out to compare the base case with the following measures found to be effective, with natural ventilation temperature control to operate windows whenever the indoor and exterior conditions are suitable:

- Curtains on all windows
- 0.5m eaves on North and South facades
- Vertical fins on East and West facades
- Shaded roof

The frequency distribution of temperatures has used as a metric to assess the efficacy of the combined effect of these measures, using rooms 1 and 2 to consider a situation with one external window and a corner configuration with two windows on mutually perpendicular walls. Figure 14 and Figure 15 illustrate the results obtained for the base case and the combined passive measures.

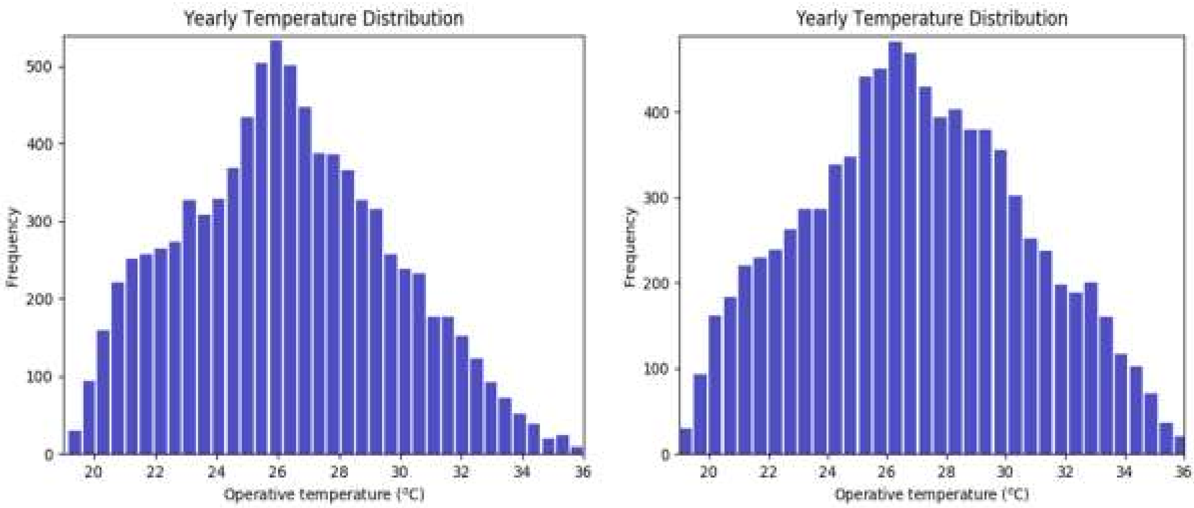


Figure 14: Yearly base case temperature distribution for room 1 and 2 respectively

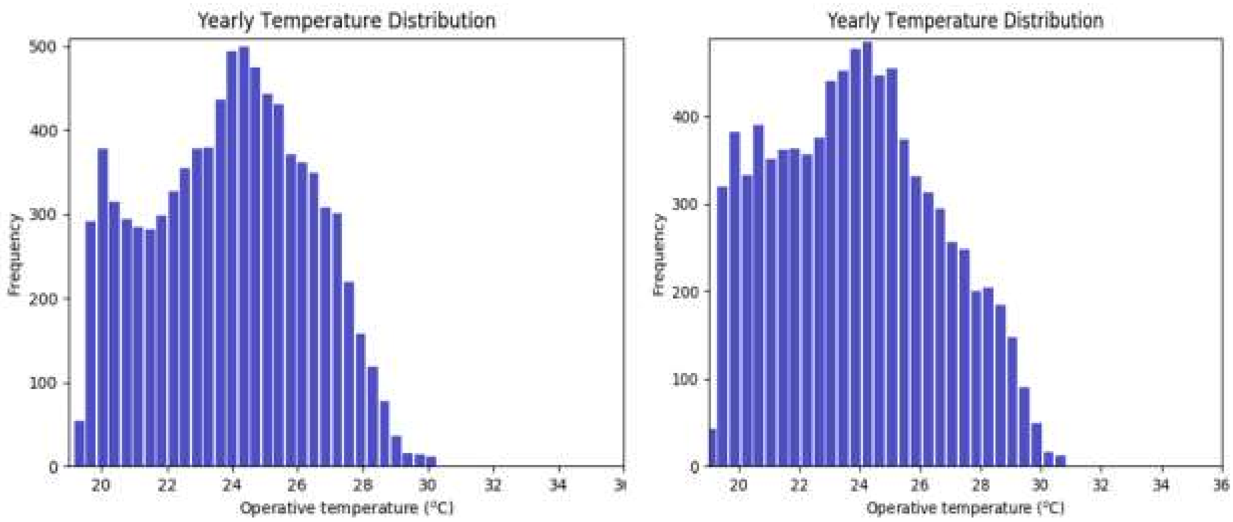


Figure 15: Yearly temperature distribution for rooms 1 and 2 respectively with selected passive measures

For the base case (Figure 14), comparing rooms 1 and 2 shows clearly the presence of more number of hours in the upper temperature ranges, which confirms the high heats gains involved with spaces with two mutually perpendicular walls with glazing as one of them will receive direct solar radiation at any point in time during the day, then creating a compounding effect of heat gains. Comparing the distribution obtained with the passive measures implemented (Figure 15), clearly shows a significant shift towards lower temperature ranges for both room configurations. Although not fully optimised, the results shows that with natural ventilation alone running in the base case, a significant number of hours of thermal discomfort (temperatures above 27°C according to ASHRAE 55 standard) is yielded, and with the integration of the passive measures, a marked improvement in indoor thermal conditions is achieved.

4.0 Experimental Results

It was not practical to field test all the passive measures. The two case studies described next refer to a two-storey house where four temperature sensors were placed to record operative temperature in two rooms (north-east and south-west facing) at ground and first floors and another case study for two east-facing adjacent rooms where curtain was left open in one room and closed in the other. The results obtained would allow to compare indoor conditions for (1) ground floor without external roof exposed to solar radiation, (2) effect on orientation (NE and SW in the house at the same story) and (3) effect of curtains on the temperature of the spaces.

4.1 Case study 1: House rooms at ground and first floors

The temperature profiles recorded for the north-east and south-west rooms at first and second floors of a house are illustrated in Figure 16 over peak summer period at 5 minutes logging interval.

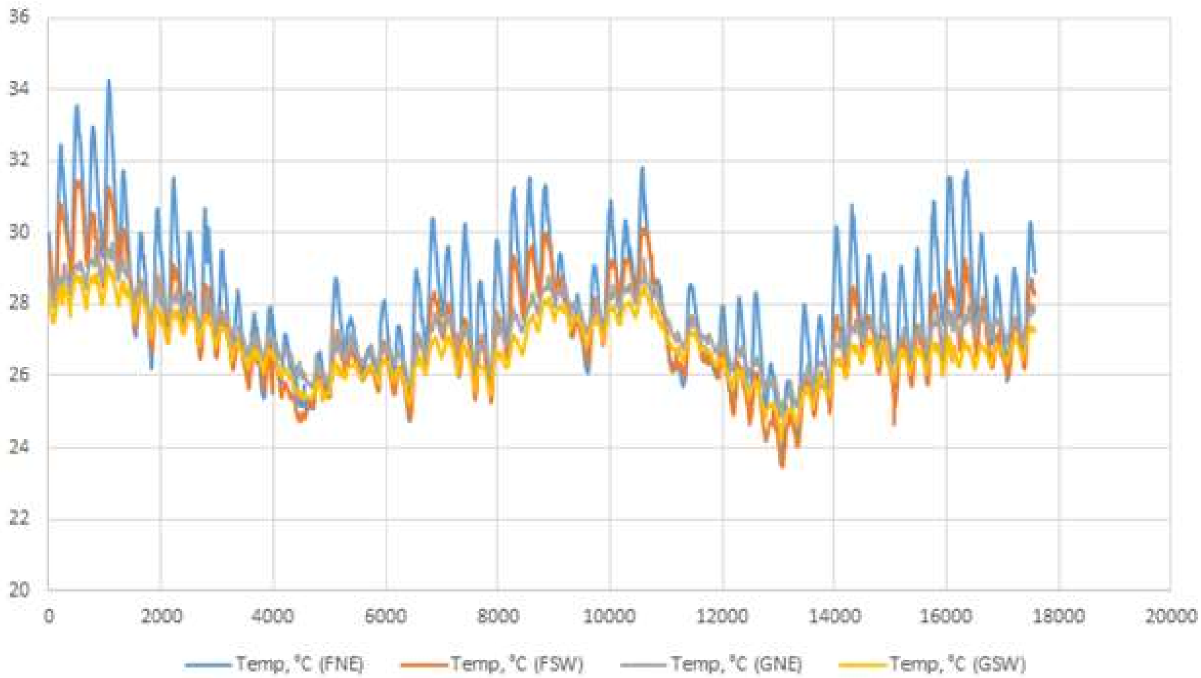


Figure 16: Influence of level and orientation on interior conditions from 15 Dec 2019 midnight to 13 Feb 2020 midnight (G=Ground, F = First Floor), x-axis with time indices over 5 minutes interval.

The difference in operative temperature for the first floor and the ground floor is clear, with up to 4°C difference between the north-east facing rooms at ground and first floors. The first floor room in the north-east orientation has no overhang whereas the ground floor room has an overhang of 1.5m depth. Moreover, at a given floor level, the influence is clearly seen with the north-east facing room having a constantly higher temperature than the south-west facing room, with up to 3°C temperature difference on the same floor.

4.2 Case Study 2: Laboratory on campus

This second case study is at the Physics lab at the university where the layout of the spaces allow for simultaneous comparison of two identical east-facing rooms, where in one case curtains was left open and closed in the other. Figure 17 shows the temperature profiles obtained from 21 November to 26 November 2019.

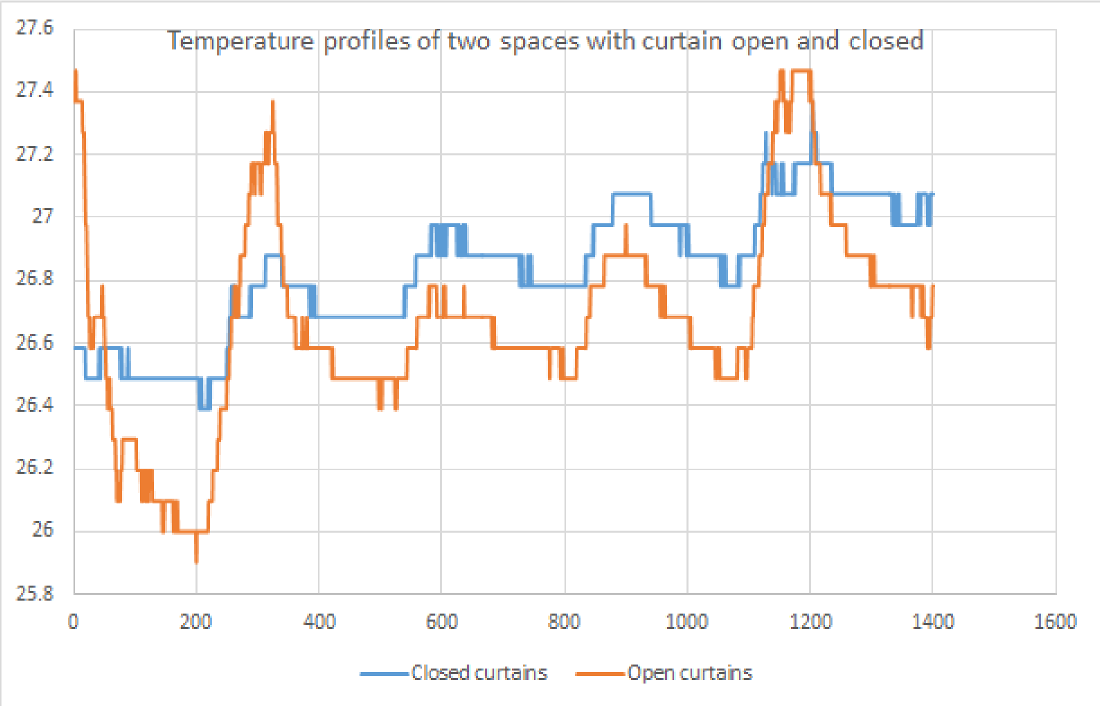


Figure 17: Investigating influence of curtains in east-facing spaces

This corresponds to summer conditions in Mauritius. The results do not show consistently high temperature with the curtains open as closed curtains also play against heat loss from the presence of persons and other heat sources in the space. Furthermore, with the curtains open, the heat loss through the glazing is also greater. In general, the higher temperatures for the curtain 'open' case were observed during the late morning condition when the sun can penetrate the interior, and a rapid dissipation of the heat during the midday and early afternoon time. This consolidates the possibility of having occupied spaces such as bedroom and living room in the east, south-east, south orientations.

5.0 Conclusions

The research project outcomes presented in this paper has allowed to produce scientific data on the performance of passive, and recommendations have been provided in the light of the heat gains and temperature profiles generated by simulation and in-situ measurements respectively. The design of homes rely on prescriptive measures, since simulation studies are not possible to assess design alternatives, and the 3x3 layout model proposed has allowed to generate representative layouts met in practice when rotated through suitable increments. The findings have allowed to better understand the complex thermal phenomena involved in the concrete constructions in Mauritius, and made it possible to set recommendations for the general public to consider in designing their home layout and remediation measures they can apply in their design before construction or as retrofits. In particular, rooms having corner configurations with glazing on each façade were found to yield as much as five times more total heat gains and a compounded effect of the two glazed openings, meaning both glazed surfaces need to be considered closely to avoid unwanted heat gains. The combined effect of shading the roof and glazing was found to be beneficial, whereas dealing with one element only generally leads to increased heat gains in the other. The equally important aspect of radiative heat from the high thermal mass concrete constructions has been evidenced in previous projects, and the diurnal variation in ambient air temperature from above 30°C during the day to below 20°C at night during summer conditions means beneficial cooling can be provided to the indoor environment and building fabric by using night cooling strategies.

One important theme that has emanated from the results obtained to be applicable to regions with both heating and cooling requirements over a year and even for regions with an overall warm climate with rooms found in east to south-west orientations, is the need to consider adaptable systems that can be deployed or removed as per requirement, either automatically or manually. With the advent of IoT sensors to collect data about processes and building automation solutions already on the market, new devices can surface to adapt passive measures relative to prevailing ambient and indoor conditions using a knowledge base to predict anticipated conditions using Artificial Intelligence learning techniques.

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